Characterizing IFE dynamics with high-resolution laser-plasma-based diagnostics

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Introduction: Need for high-rep-rated high-resolution IFE diagnostics

The production of large amounts of energy for global consumption, in a sustainable and environmentally safe way, is still an unresolved problem. Nuclear fusion is considered one of the most promising ways of achieving this. However, fusion energy production is a complicated process, which requires the maintenance of fuel in the form of a high temperature plasma. This task requires the advance of our understanding of fundamental plasma science, ability to diagnose with high precision and control this plasma under the extreme conditions. The diagnostics need to resolve with high accuracy the dynamic behavior of plasma and electromagnetic fields, their evolution in space and in time. This is of great importance from the point of view of controlling this plasma and predicting how it will behave in given experimental setups. In other words, for a given plasma setup the diagnostics should be able to probe density, velocity distributions of electrons and ions, electric and magnetic fields, and guide a route for control and exploitation. It should be emphasized that the diagnostics need to access the spatial (micro-scale) and temporal time scales (picosecond and below) of interest, at repetition rates to either match the IFE experiments or surpass them in order to access new regimes of diagnostic stabilization through active feedback and ML/AI concepts. In fact, a separate whitepaper titled "*High repetition rate diagnostics with integrated machine learning analysis for a new paradigm of actively controlled Inertial Fusion Energy experiments*" is submitted by G. Scott (LLNL) and co-authors, where ML/AI and high-rep-rate concepts are further explored. In terms of diagnostics, and given the typically high density and temperature of fusion-plasma high-energy particle and photon beams, the high-energy particle and photon diagnostics generated in laser-plasma interactions are among the most promising candidates for diagnostic development.

Ultra-intense laser pulses (at intensities where electrons quiver at relativistic velocities) can drive attractive particle and high-energy photon sources through their interaction with gas or solid targets. Photons are emitted both during the electron & ion acceleration process inside the plasma, and during post-accelerator particle beam manipulation with external magnetic fields and/or external laser pulses. Because the plasma can temporarily sustain extremely large fields, the laser-plasma based particle and photon sources are typically compact, the radiation beams are extremely short (femtosecond to picosecond) and intense, and the radiation pulses are intrinsically synchronized on the femtosecond time scale to other pump and probe sources. This facilitates integration of high resolution probes with IFE research/drivers.

In this white paper, we highlight the relevance that diagnostic probes derived from laser-plasma accelerators can bring to the IFE community [Albert2014, Albert2016]. Applied to high-energy density targets, they give information on electromagnetic fields, material density, and their associated dynamics, and together are an integral part of comprehensive plasma science platforms. Each type of laser-plasma-accelerator probe can be produced with small fractional splits of the lasers that drive other experiments, or with femtosecond lasers of modest scale which can be easily locked to a common oscillator, facilitating implementation in HED/IFE experiments. A summary of the achieved or anticipated source parameters is given at the end.

Picosecond proton beams

Interaction of an intense laser pulse with solid-density material generates proton and heavier ion beams from several different mechanisms, which depend on the initial laser parameters and target conditions. In addition to advanced and promising schemes [Bulanov2016] such as Radiation Pressure Acceleration (RPA), Magnetic Vortex Acceleration (MVA), and Directed Coulomb Explosion (DCE), the most experimentally studied mechanism is the Target Normal Sheath Acceleration (TNSA), where the laser pulse produces and heats a plasma on the target surface with thermal electrons penetrating through the target, forming a sheath at the rear surface. This creates a strong electric field in the area that accelerates ions from the rear side of the target [Wilks2001]. These proton beams have unique properties such as short pulse duration (picosecond at the source), low emittance ($5x10^{-3}$ π mm mrad) [Cowan2004], high degree of collimation, and high flux, making them suitable for various applications [Roth2001, Borghesi2001, Patel2003].

One promising proton and ion application of relevance to IFE is imaging with high spatial and temporal resolution to probe high density matter. For example, proton radiography can image the evolution of electromagnetic field distribution on the order of GV/m (MG) [Steinke2009, Sokollik2008]. The onset and growth of hydrodynamic instabilities and shock wave formation can be probed, which are of interest to fusion energy research as such instabilities severely impact the implosion symmetry.

During the compression phase, target material becomes dense plasma through the Warm Dense Matter (WDM) state, which is a challenging regime due to uncertainties in the theoretical model and lack of experimental investigations in this regime. High energy density and short bunch ion beams can be used to isochorically heat solid-density matter to WDM state before hydrodynamic expansion and thus provide a path to generate and diagnose WDM conditions [Zylstra2015,Apiñaniz2021].

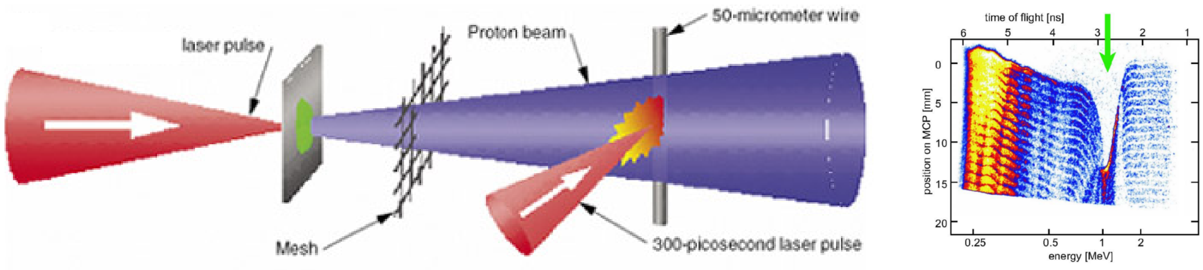

Figure 1: (left) Proton beams can be used to probe the field structure of targets. (right) Field structure is visible as deflection, in this example using time of flight of 1.2-2.4 MeV protons to obtain a temporal profile of the effect a laser irradiation at 10^{18} W/cm^2 (at the time shown by the green arrow) [Sokollik2008]. This complements the detailed structural information available from X-ray probes.

Betatron X-ray probes

Electrons in laser plasma accelerators are not only accelerated to 100s of MeV by the periodic plasma wakefield [Esarey2009], but also kept ‘on track’ by the wakefield’s focusing force. This causes betatron oscillations, which result in the emission of X-rays in the keV-10s keV range with a synchrotron-like spectrum. Such X-rays have intrinsic few-fs duration, micron source size, mrad divergence and >1e8 photons/shot [Kneip2010, Hussain2019, Kettle2019, and references therein]. The small source size combined with its small divergence have been shown to enable propagation-based phase-contrast imaging (PCI). In other words, the source is spatially coherent. PCI is specifically sensitive to small density gradients in the target which bend the rays into darker and brighter interference patterns. The above specifications make betatron x-rays from laser plasma accelerators an attractive candidate for imaging short-lived events, e.g., in HED science, lab-astrophysics and IFE, at high resolution in a single shot.

Mono-chromatic Thomson-scattered X-ray photons

For many applications, including in IFE, monoenergetic x-rays and gamma-rays in a harder x-ray regime are highly desirable due to their larger penetration depth. Thomson scattering (or Inverse Compton Scattering) is a technique where a relativistic electron beam, e.g. from a compact laser plasma accelerator, is brought to collision with a second laser pulse, see Figure 2. Due to the relativistic Doppler effect, scattered photons from the second laser pulse can be shifted in energy up to $\hbar\omega_{Laser}4\gamma^2$. This method allows production of compact, collimated, monoenergetic photon sources from few-100 keV up to the 10 MeV range [Albert2014, and references therein]. The photon energy is easily adjusted by tuning the electron beam energy. Such photons would enable probing of compressed IFE cores at micron and femtosecond resolution. Plasma accelerators can make such sources available using few-Joule lasers and 10m-scale space compatible with IFE facilities, in contrast to conventional sources which are too large for these applications. Other properties are shared with betatron sources described above and make laser driven Thomson sources an attractive complementary source to others mentioned in this paper.

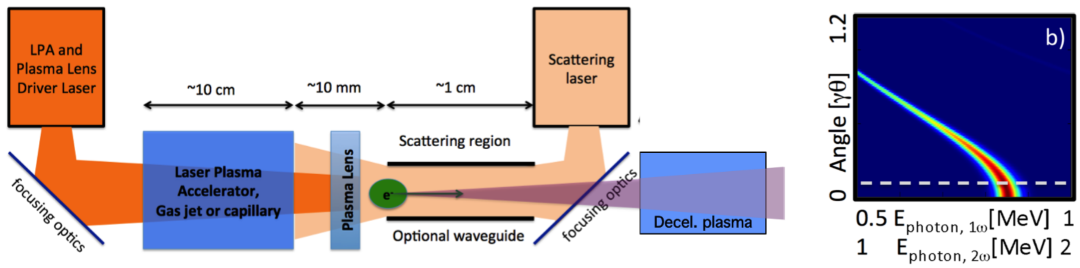

Figure 2: (left) A compact Thomson photon source would include LPA-based cm-scale electron acceleration to ~0.5 GeV, a plasma-based cm-scale electron lens to re-collimate the beam and reduce divergence, a plasma waveguide to extend scattering for increased yield (photon beam purple), a plasma mirror, and deceleration to reduce shielding needs. (right) Collimated, narrow-bandwidth photon spectrum (simulated) [Rykovanov2014].

X-rays from FELs

XFELs, compared to other sources of ultra-short duration x-rays, provide photon beams with unparalleled brightness (~10 orders of magnitude brighter than conventional synchrotrons) with energies up to 25 keV and pulse durations at the attosecond-scale [Pellegrini2016]. As such, they have proved to be an invaluable tool in probing matter under extreme conditions in unprecedented detail [Bostedt2016]. The availability of a very hard x-ray FEL at a dedicated spherical compression facility, like NIF, could have a transformative impact on the development of IFE technologies. Bringing an XFEL to such a facility, however, is non trivial as they tend to be billion dollar machines requiring several kilometers of real estate to build. LPAs offer an opportunity to circumvent this challenge through a drastic rescaling of the XFEL infrastructure. An XFEL requires a very high brightness electron beam that can be accelerated to ~10 GeV. LPAs are proving to be quite capable of producing beams with brightnesses exceeding state-of-the-art photo injectors [Manahan2017] and can accelerate to ~10 GeV in a distance of several centimeters [Gonsalves2019]. Thus, LPAs offer a substantially reduced barrier to designing and building an XFEL dedicated to augmenting IFE facilities. Recently, laser-wakefield FEL lasing at 27 nm was achieved [Wang2021].

Electron beam probes

Laser plasma accelerators can produce MeV to GeV-class electron pulses with 100 pC level charge, few-fs duration, micron source size and mrad divergence in very compact tabletop machines. Such electron beams are well suited to probe electro-magnetic fields that occur in HED scenarios, including in IFE, where fields can play critical roles including seeding and formation of plasma instabilities. An electron pulse propagating through an HED object can take a projected (integrated) femtosecond snapshot of the object's field configuration, and can have deeper penetration than proton probes. Information from this high resolution electron deflectometry diagnostic can reveal critical dynamics and serve as an important benchmark, since many theoretical predictions and numerical calculations for IFE experiments are based on pure hydrodynamics of neutral material, i.e., neglecting fields and charge separation altogether. While largely unexplored, a recent demonstration used plasma-wakefield electron beams to probe electric and magnetic fields in a secondary laser-driven wakefield structure [Zhang2017]. Application to IFE targets could involve probing the relevant field environment and dynamics exterior to the solid-density core.

Sources Summary:

Laser-Plasma Radiation Source	**Energy range**	**Notable parameters**	**Current Readiness**	**R&D to yield improvements**
Protons	~1-100 MeV	(sub-)Nanosecond duration, broadband, >1e8 protons/shot	Mature demonstrations (TNSA)	Improve laser pulse contrast, rep rate, optimize solid target design. Explore new acceleration regimes
Betatron X-rays	1-20 keV Broad spectrum	Femtosecond, broadband, Spatial coherence, >1e7/shot	Mature demonstrations	Minor optimizations possible for source size, flux, cut-off energy, and stability
Thomson-Scattered X-rays	100 keV - 10 MeV quasi-monoenergetic	Femtosecond, quasi mono-energetic, 1e8/shot	Mature demonstrations	Reduce bandwidth through accelerator optimization and scatter laser shaping
FEL X-rays	~10-30 keV mono-energetic	Sub-femtosecond, intense, spatial & temporal coherence, 1e11/shot	Soft X-ray milestone demonstration	For harder X-rays: develop high-brightness beams, advanced phase-space manipulation, higher energy beams (~10 GeV)
Electrons	MeV-GeV	Few-fs beams, 10-100 pC, %-level energy spread	Mature and extensive demonstrations	Improve stability, increase repetition rate, and expand on precision & control

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